Framework for a Gap Analysis of Aquatic Ecosystem Health

By Judson W. Harvey, Mark M. Dornblaser, A. Robin Stewart, Allen C. Gellis, Christopher H. Conaway, Nancy T. Baker, Jeramy R. Jasmann, Deborah A. Repert, Richard L. Smith, Elizabeth J. Tomaszewski, and Kimberly P. Wickland

Chapter A of

Knowledge Gaps and Opportunities in Water-Quality Drivers of Aquatic Ecosystem Health

Edited by Judson W. Harvey, Christopher H. Conaway, Mark M. Dornblaser, Allen C. Gellis, A. Robin Stewart, and Christopher T. Green

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Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
cubic mile (mi^3)	4.168	cubic kilometer (km^3)
billion gallons (Ggal)	0.003785	cubic kilometer (km^3)
	Mass	
ounce, avoirdupois (oz)	28.35	gram (g)
pound, avoirdupois (lb)	0.4536	kilogram (kg)
ton, short (2,000 lb)	0.9072	metric ton (t)

International System of Units to U.S. customary units

Multiply	By	To obtain
	Length	
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
	Area	
square kilometer (km^2)	0.3861	square mile (mi^2)
	Volume	
liter (L)	0.2642	gallon (gal)
cubic kilometer ($km^{3)}$	2.64172	billion gallon (Ggal)
	Mass	
gram (g)	0.03527	ounce, avoirdupois (oz)
kilogram (kg)	2.205	pound avoirdupois (lb)
metric ton (t)	1.102	ton, short [2,000 lb]

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as °F = (1.8 × °C) + 32.

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as °C = (°F – 32) / 1.8.

Supplemental Information

Concentrations of chemical constituents in water are given in either milligrams per liter (mg/L) or micrograms per liter (µg/L).

Abbreviations

DOE	U.S. Department of Energy
EPA	U.S. Environmental Protection Agency
FERC	Federal Energy Regulatory Commission
HAB	harmful algal bloom
IWP	USGS WMA Integrated Water Prediction program
IWAAS	USGS WMA Integrated Watershed Availability Assessments Program
MMI	macroinvertebrate multimetric index
NASA	National Aeronautics and Space Administration
NGO	non-governmental organization
NOAA	National Oceanic and Atmospheric Administration
NSF	National Science Foundation
NWQP	USGS National Water Quality Program
RSQA	USGS Regional Stream Quality Assessment
USACE	U.S. Army Corps of Engineers
USDA	U.S. Department of Agriculture
USGS	U.S. Geological Survey
WMA	USGS Water Resources Mission Area

Chemical Symbols

Sb	antimony
As	arsenic
Bi	bismuth
Cd	cadmium
C	carbon
Cr	chromium
Co	cobalt
Cu	copper
Fe	iron
Pb	lead
Li	lithium
Mn	manganese
Hg	mercury
Mo	molybdenum
O	oxygen
Se	selenium
Ti	titanium
Zn	zinc

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Chapter A

Framework for a Gap Analysis of Aquatic Ecosystem Health

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Introduction

Gaps in scientific knowledge limit our ability to predict water quality effects on the health of aquatic ecosystems. This report summarizes key gaps and describes approaches to address them. In 2020 the Eco-Health Gap Analysis team for the USGS Water Resources Mission Area's National Water Quality Program (NWQP; https://www.usgs.gov/programs/national-water-quality-program) discussed potential topical areas. The following four key topical areas were selected for an in-depth gap analysis of water-quality drivers of aquatic ecosystem health and make up the remaining chapters of this report: coupled nutrient-carbon cycle processes and related ecological-flow drivers (Chapter B), anthropogenic and geogenic contaminant bioexposures (Chapter C), fine sediment drivers (Chapter D), and freshwater salinization (Chapter E). In each chapter, there is a discussion of the scientific gaps, approaches, and timelines to address the gaps.

What is Aquatic Ecosystem Health?

Many factors control the structure, function, and persistence of aquatic communities. Healthy aquatic ecosystems are characterized by flow and habitat conditions, water quality, and food availability that sustain the biological community close to the state of an undisturbed "reference community" (Baldaccini and others, 2009; Durbecq and others, 2020). Well-functioning river corridors often include naturally varying flows, geomorphic complexity, and diverse sediment conditions. Also important are appropriate levels of light, organic matter inputs, and other factors that support feeding, dispersal, nesting, and rearing of aquatic consumers. Refugia provide a buffer from excessive predation, extreme flows, and physiochemical stressors.

Natural aquatic communities undergo a variety of chemical, biological, and hydrological disturbances. Chemical disturbances include excessive inputs of salinity, toxic elements, fine sediment, organic matter, or nutrients from the watershed or river corridor. Biological disturbances may stem from extended periods of low dissolved oxygen (Blaszczak and others, 2022) and high temperature (Briggs and others, 2018) that impose physiological stress, as well as whole-system disruptions of aquatic metabolism that include excessive, oxygen-depleting algal blooms (Glibert and others, 2010), blooms that are toxic (Burford and others, 2020), or blooms of undesirable species that are less nutritious for higher trophic levels (Giblin and others, 2022). Another major cause of biological disturbances is invasive species that out-compete native species and disrupt food webs. Hydrologic disturbances include changes to the natural flow regime (Poff and others, 1997) and to the natural sediment regime (Wohl and others, 2015) stemming from more frequent or ill-timed floods and droughts as well as changing seasonal patterns of high and low flows. Natural aquatic communities typically can recover from temporary levels of moderate stress. However, hydrologic disturbances may interact with chemical and biological disturbances to compound and prolong the effects on ecosystems.

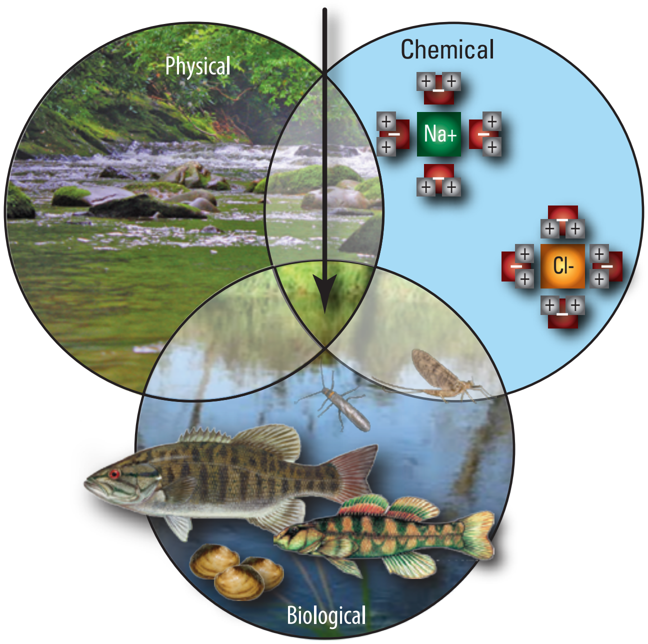
Human alteration of aquatic systems is increasing the occurrence and persistence of stressors. Industrial and agricultural activities have radically changed the global amount and distribution of atmospheric carbon dioxide (CO_2) (Canadell and others, 2007), reactive nitrogen (N) in the biosphere (Galloway and others, 2008), and distribution of phosphorus (P) (Gilbert, 2009), leading to reorganization of biological communities (Finzi and others, 2011). Extreme events related to climate change (for example, wildfires, floods, and droughts) interact with local land-use practices to influence concentrations of salinity and anthropogenic and geogenic contaminants, leading to negative impacts on aquatic ecosystems (Kolpin and others, 2002; Barnes and others, 2008; Focazio and others, 2008; Chapman and others, 2010; Bradley and others, 2016; Kaushal and others, 2018). Human-altered runoff regimes that increase the frequency of floods and droughts also may eliminate favorable sub-habitats and expose aquatic organisms to higher concentrations of contaminants. Land use effects are of particular concern where they influence flow, sediment sources, riparian shading, and the biogeochemistry of headwater streams as well as the larger river channels. Important functions of streams and rivers are enabled by interactions with subsurface hyporheic zones and with riparian zones and floodplains, elements that together with the main channel comprise the river corridor (Harvey and others, 2019). River corridor interactions collectively influence a broad array of water quality and aquatic ecosystem functions (Gilliam 1994; Wohl and others, 2015; Golden and Hoghooghi, 2017; Lynch and others, 2019; Harvey and others, 2019). Flow alterations and land use changes influence longitudinal and lateral connectivity of river corridors, capacity of riparian buffers for water purification, bank erosion and sediment supply, and hyporheic and riparian ecosystem functions that facilitate the storage and transformation of organic matter, nutrients, fine particulates, and contaminants (Wymore and others, 2023).

How is Aquatic Ecosystem Health Assessed?

Physical, chemical, and biological factors act together to influence the structure and function of aquatic communities (Carlisle and others, 2013) (fig. A1). Consequently, despite efforts to build simple criteria based on single factors, such as nutrient concentrations that specify eutrophication (for example, Dodds and Smith, 2016) or flow statistics that quantify flow alteration (for example, Poff and others, 2010), the signature of a healthy aquatic system is in fact quite difficult to assess. An alternative is to use an integrative metric that broadly characterizes aquatic health. For example, benthic macroinvertebrates in streams play a key role in processing detritus and providing food for higher consumers in healthy aquatic ecosystems. Sampling the benthos in thousands of streams provided the data for a macroinvertebrate multimetric index (MMI) that assesses health based on taxonomic richness, diversity, balance among feeding groups and habitat requirements, and pollution tolerance relative to reference streams (U.S. Environmental Protection Agency [EPA], 2020b). The resulting MMI provides a transferable measure of ecosystem health that is temporally persistent and can be consistently applied across the Nation. Other biological indicators also are used, for example, fish community metrics, as well as physiochemical indicators (nutrients, salinity, temperature), and physical habitat indicators (for example, riparian condition, excess fine sediment) (EPA, 2020b).

Aquatic ecosystem health is also assessed in terms of societal interests in the services and beneficial uses that are accrued. Scientific information can inform decisions by stakeholders and support investments to protect or enhance those valuable services. Ecosystem services are evaluated according to the functions performed, including water storage and purification, biological production and fisheries, biodiversity, carbon storage, recreational opportunities, and values of public natural spaces and private lands (Brauman and others, 2007). Stakeholder interest may range broadly from managing declines in specific biological communities (for example, endangered fisheries), managing water supply for human beneficial use while also reserving flows for biological

***A.* Aquatic Ecosystem Health**



B

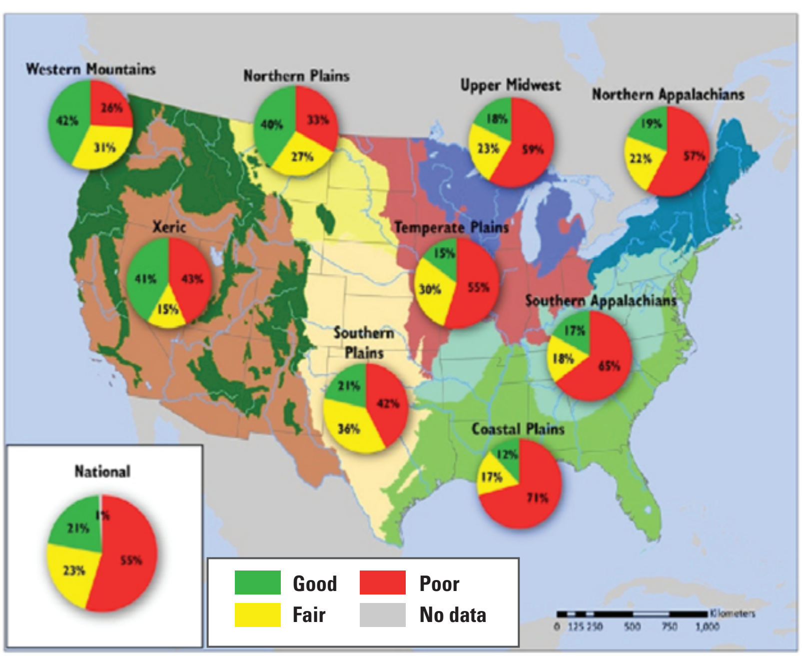


Figure A1. Diagrams of aquatic ecosystem health assess the structure and function of biological communities responding to physical and chemical factors and biological needs and tolerances. *A*, Venn diagram of physical, chemical, and biological factors acting together to influence the structure and function of aquatic communities (Carlisle and others, 2013). *B*, Multi-factor measures such as macroinvertebrate multimetric index (MMI) indicate that more than half of the stream miles in the continental United States rate as being in poor ecological condition, as shown in pie diagrams against mapped U.S. Environmental Protection Agency (EPA) level II ecoregions. The highest ecological impairment occurs in the Coastal Plain ecoregion (71 percent [%]) and lowest in the Western Mountains ecoregion (26%). Modified from EPA (2020b). Na^+, sodium cation; Cl^-, chlorine anion.

communities, managing contaminant loads to protect biological communities and sustain recreational uses, as well as managing waterways to address concerns about odor and aesthetic appeal.

Federal Agency Role in Aquatic Ecosystem Health

A summary understanding of the U.S. Geological Survey's (USGS's) mission among Federal agencies is the basis from which to begin knowledge gap analyses. Throughout the fall of 2020 the Eco-Health Gap Analysis team for the USGS Water Mission Area's National Water Quality Program (NWQP; https://www.usgs.gov/programs/national-water-quality-program) discussed potential topical areas. Scientific guidance in water quality and ecosystem health issues for the United States comes from Federal agencies such as the U.S. Environmental Protection Agency (EPA), USGS, U.S. Department of Agriculture (USDA), National Oceanic and Atmospheric Administration (NOAA), U.S. Department of Energy (DOE), U.S. Army Corps of Engineers (USACE), National Aeronautics and Space Administration (NASA), Federal Energy Regulatory Commission (FERC), and the National Science Foundation (NSF). The role of the USGS and other agencies is to carry out the necessary monitoring, laboratory-based experiments and modeling required to create the best framework to guide regulatory agencies, States and municipalities, non-governmental organizations (NGOs), and other stakeholders in their decision-making about water resources. This vitally important role is intended to ensure that regulations and best management practices are effective, including the protection of ecosystem health.

The scientific information provided by Federal agencies is used to design and implement protective management actions. Regulatory responsibilities are primarily in the EPA, FERC, and the USACE which have regulatory authority over wastewater releases and physical alteration of waterways, as well as river and reservoir infrastructure and operations. The EPA tracks and compiles State reporting of water quality impairments of waterways (EPA, 2017) and has established exceedance criteria for contaminants to protect aquatic organisms. Many of those criteria target specific organisms and life stages to protect against contaminants such as pesticides, metals, and emerging contaminants. Notably, many of EPA's exceedance thresholds for specific compounds are lower for ecological health than for human beneficial use.

Declines in aquatic ecosystem health are often the result of multiple factors. For example, the biological impairment of benthic macroinvertebrate communities is often related to nutrients, salinity, and temperature, but is almost twice as likely to be rated poor when levels of excess fine sediment are high (EPA, 2020a). Federal agency programs such the USGS Water Resources Mission Area (WMA) Regional Stream Quality Assessment Program (RSQA, https://www.usgs.gov/tools/regional-stream-quality-assessment-rsqa) have demonstrated how the dominant physical and water-quality drivers of aquatic health can be identified. For example, alteration of streamflow, particularly in the western United States, often is found to operate in concert with water-quality drivers to impair ecological health (Carlisle and others, 2013). Identifying the multiple, key factors controlling aquatic health is imperative to serve stakeholders charged with decisions and investments to protect ecological resources across the Nation.

Gaps in Understanding of Water Quality Threats to Aquatic Ecosystem Health

How a Gap Analysis Can Serve the USGS

Presently the USGS WMA focuses on measuring water flow and water quality in a nationally consistent manner to support stakeholder information needs to manage water resources. In addition to making the measurements, the USGS analyzes spatial and temporal trends and models source areas and movement of constituents of concern to receiving waters. Furthermore, the USGS characterizes hydrologic alterations of streamflow and its role in structuring aquatic communities. USGS also interacts directly with local stakeholders that support specific stakeholder interests in current programs and priorities.

USGS's expertise in hydrologic flows, constituent source areas, and movement of constituents through watersheds does not serve all stakeholder needs, especially from an ecosystems health perspective. Quantifying source areas and loads, alone, cannot provide a holistic understanding of the water quality drivers of ecosystem health. That understanding served as a starting point for our gap analysis.

A knowledge and data gap analysis can propose topical areas and priority opportunities that are uniquely suited to a particular agency's mission. Here the WMA's NWQP carried out the gap analysis with an aim to serve WMA's Integrated Water Prediction (IWP) (https://www.usgs.gov/mission-areas/water-resources/science/integrated-water-prediction-iwp) and Integrated Watershed Availability Assessments (IWAAS) programs (https://www.usgs.gov/mission-areas/water-resources/science/integrated-water-availability-assessments-iwaas). Both parent programs emphasize the identification of causal factors with IWP focusing on forecasting future outcomes. Our gap analysis focused on prioritizing new capabilities beyond the current expertise of USGS in streamflow and constituent concentration trends toward developing integrated capabilities for assessment and modeling of the water-quality drivers of aquatic ecosystem health (table A1).

Many important topics for ecosystem health are not in the purview of the USGS WMA. For example, building contaminant exceedance criteria for specific organisms and life stages, although crucial for establishing contaminant exceedance criteria for ecosystems, is a task that is best suited for EPA's combined research and regulatory authority that supports specialty areas through research contracting with universities. Similarly, although pathogens rank highly as an impairment of beneficial uses of aquatic ecosystems, the USGS WMA currently has limited involvement compared to other agencies.

Table A1. Opportunities for the U.S. Geological Survey (USGS) Water Mission Area (WMA) in aquatic ecosystem health.

[WMA, USGS Water Resources Mission Area (https://www.usgs.gov/mission-areas/water-resources); NWQP, USGS WMA National Water Quality Program (https://www.usgs.gov/programs/national-water-quality-program); IWP, WMA Integrated Water Prediction (https://www.usgs.gov/mission-areas/water-resources/science/integrated-water-prediction-iwp); IWAAS, WMA Integrated Watershed Availability Assessments (https://www.usgs.gov/mission-areas/water-resources/science/integrated-water-availability-assessments-iwaas.]

What	Who	Why	Where	How
Ecosystems are vulnerable to short-term disturbances and long-term alterations that threaten ecosystem health and societal values including water purification, species diversity, high-value recreational species, safe recreational waters, and drinking water.	WMA WQP developing capabilities for IWP and IWAAS programs. Priorities reflect equally: (1) stakeholder rank of importance, (2) USGS capabilities and growth opportunities, and (3) current data availability.	New capabilities needed in data collection and analysis to advance beyond characterizing trends of single constituents in streamflow to inform predictions of eco-health. Serve timely information to support stakeholder decision making and prioritization of regulatory and management actions to counter threats.	All waters, surface and subsurface, that affect surface water availability and quality now, and for decades in the future. Assessments and models vary in spatial extent from individual watersheds to the Nation, at timescales ranging from days to decades, to inform predictions of eco-health.	Integrated assessments and models of water quality drivers of eco-health. Products may involve:(1) early warnings for recreational users, water intake operators, and other stakeholders (2) vulnerability assessments for landowners, managers, and other stakeholders

Potential Topics for an Eco-Health Gap Analysis

During discussions of potential topical areas, the ecosystem health gap analysis team for the WMA Water Quality Program discussed a broad array of potential topics. For example, the team discussed gaps in environmental toxicology that limit opportunities for managing ecosystems. To assess ecological toxicity more fully, it was argued that more process-based research is needed to improve predictions of organism bioexposure pathways through diet or direct uptake (Mebane and others, 2020). Such work can classify key bioexposure pathways to emerging contaminants of concern, and to broadly characterize uptake mechanisms for classes of contaminants at various levels of the food web. Such information can be used to refine how bioexposure and bioavailability are measured, managed, and regulated. The USGS could assist collaborators in expanding the data sources for modeling the fate of many anthropogenic and geogenic contaminants, including innovative modeling of anthropogenic contaminants. An example is advanced model tracking of wastewater inputs to downstream locations (Barber and others, 2022).

The team also discussed how historically the USGS and other agencies have typically modeled only single contaminant threats, yet the most common threats to aquatic ecosystems in the United States are attributed to the simultaneous presence and mixture of several contaminants (Masoner and others, 2019). Salinization of the Nation's freshwaters is one of the most widespread manifestations (Kaushal and others, 2018). It is a complicated problem for ecosystem health because of the broad-based "chemical cocktails" that can be involved and because of the difficulty in anticipating outcomes for aquatic communities (Dugan and others, 2017). There are differential lethal and sublethal effects of salinity on specific organisms, as well as higher level effects on community structure and function, in addition to the ancillary effects of changing salinity on mobilization of contaminants stored in sediments. All of these have potentially cascading effects on downstream ecosystems. Likewise, many EPA Superfund sites hosting a myriad of industrial contaminants are in floodplains, exacerbating the potential for rapid mobilization and spreading of contaminants to downstream areas.

There is growing recognition of the need for multi-factor controls for aquatic health involving physical, biogeochemical, and biological interactions that threaten aquatic ecosystems (Community Coordinating Group on Integrated Hydro-Terrestrial Modeling, 2020). For example, widespread deoxygenation has occurred in warming temperate rivers of the United States and Europe (Zhi and others, 2023) with steeper trends in urban and agricultural landscapes consistent with hydrologic and biogeochemical drivers (Blaszczak and others, 2022). Excessive algal growth can arise from the coupled influences of higher nutrient inputs, moderate to high light availability, and extended water residence times in rivers regulated for navigation in the intensively farmed Midwestern United States (Giblin and others, 2022). Excess nutrients and organic carbon (OC) may derive from watershed activities such as agriculture and rangeland management, urbanization, and stormwater management, as well as wildfire, forest roads and related forest management practices (Bernhardt and others, 2022). Excess nutrients and OC also may be derived from within the river network, for example, from mobilization from reservoir or stormwater pond sediments (Taguchi and others, 2020) or from release from storage in living algal biomass or from storage in river pools or riparian zones. Dams not only alter the flow regime but also play a role by storing nutrients and fine particulate organic matter that may later be released to fuel excessive algal blooms (Wang and others, 2019).

In addition, excessive algal blooms can overload aquatic systems with labile organic matter that buries coarse-grained biological habitat with fine sediment, and consumes oxygen, sometimes leading to hypoxia and fish kills.

The result of anthropogenic alterations has been eutrophication of surface waters—major shifts in metabolism and trophic dynamics that alter aquatic food webs in rivers and their downstream receiving waters including lakes, reservoirs, and estuaries (Dodds and Smith, 2016). Larger and longer lasting algal blooms can lead to more frequent recreational area closures, fouled water treatment operations, and releases of biological toxins that threaten wildlife, pets, and humans (Glibert, 2017).

Eutrophication of surface waters accounts for the highest number of reported impairments by EPA. Eutrophication is not often reported directly. Instead, eutrophication is often reported in terms of the expected drivers or associated water-quality changes, such as excessive nutrients (ranked number 2 in terms of the number of reported impairments) and oxygen depletion by organic enrichment (ranked number 4) (EPA, 2017). Those broad water-quality impairments are often accompanied by related broad-based water-quality impairments such as salinity (ranked number 12). Notable exceptions to those broad-based water-quality impairments are specific anthropogenic and bio- or geogenic contaminants, such as pathogens (ranked number 1); trace metals, such as arsenic (As), copper (Cu), and selenium (Se) (ranked number 3); and mercury (Hg) which ranked number 7 among all reported impairments (EPA, 2017).

Other highly ranked impairments in the Nation that relate to eutrophication and to habitat suitability for high-value aquatic species include high total suspended solids (ranked number 6) and high temperature (ranked number 10). Fine grained sediment (less than 0.063 millimeter [mm]) is a key impairment of United States waterways that reduces water clarity, clogs bed sediments, raises temperature, and increases biological oxygen demand that can suffocate fauna and fish eggs (Cluer and Thorne, 2014). Also, longer and hotter fire seasons in the western United States are increasing the loading of fine sediment with a high black carbon content to rivers (Wagner and others, 2015) which stresses stream ecosystems by increasing turbidity and biological oxygen demand. In addition, increased sedimentation in western rivers may exacerbate channel aggradation and flooding (Wagner and others, 2015). In the Northeastern United States, where a wetter and warmer climate is predicted, an important question is whether increased loadings of sediment-associated nutrients (Noe and others, 2020) will exacerbate algal blooms and hypoxic events.

Nutrient and fine sediment contamination and harmful algal blooms (HABs), acting together, can substantially affect local economies throughout the Nation. For that reason, hypoxia and HABs were identified by a recent workshop of seven Federal agencies and many universities addressing the need for integrated hydro-terrestrial modeling to serve stakeholders (Community Coordinating Group on Integrated Hydro-Terrestrial Modeling, 2020). Alongside floods and western water, hypoxia and HABs were proposed as one of three grand challenges by the Community Coordinating Group on Integrated Hydro-Terrestrial Modeling (2020). Integrated hydro-terrestrial modeling of coupled constituents could support development of early warning capabilities for excessive algal blooms and hypoxia.

Selected Topical Areas for the Gap Analysis

Team deliberations during the fall of 2020 identified four key topical areas for an in-depth gap analysis. Team selections were vetted in discussions and presentations with a wider set of USGS colleagues. Many potential topics were discussed that could play an important role in improving USGS service to stakeholders who need the information to assess potential effectiveness of management strategies to protect ecosystem services and water supply.

The following four key topical areas were selected for an in-depth gap analysis of water-quality drivers of aquatic ecosystem health:

1. Coupled nutrient-carbon cycle processes and related ecological-flow drivers,
2. Anthropogenic and geogenic toxin bioexposure,
3. Fine sediment drivers, and
4. Freshwater salinization.

The eco-health gap analysis that follows assesses for each of the selected topics the (1) status of knowledge and key limitations, (2) identification of specific gaps, (3) approaches to address gaps, (4) prioritization of gaps with timelines, and (5) potential outcomes for water-quality stakeholders. Topics included a discussion of the role of data collection, issues of scale and transferability, and appropriate analysis approaches to address stakeholder needs for scientific information about water-quality and ecological-flow-regime (“eco-flow”) drivers of aquatic ecosystem health (Suen and Eheart, 2006). As the science and stakeholder needs evolve, there is need for program evolution to keep pace—hence this gap analysis with proposed approaches for moving forward in addressing issues today as well as emerging issues for future aquatic ecosystem health.

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